

Published in final edited form as:

Nat Hum Behav. ; 1: 896–910. doi:10.1038/s41562-017-0244-9.

The default network and the combination of cognitive processes that mediate self-generated thought

Vadim Axelrod^{1,2}, Geraint Rees^{2,3}, and Moshe Bar¹

¹The Gonda Multidisciplinary Brain Research Center, Bar Ilan University, Ramat Gan, 52900, Israel

²Institute of Cognitive Neuroscience, University College London, London, WC1N 3AR, UK

³Wellcome Trust Centre for Neuroimaging, University College London, London, WC1N 3AR, UK

Abstract

Self-generated cognitions, such as recalling personal memories or empathizing with others, are ubiquitous and essential for our lives. Such internal mental processing is ascribed to the Default Mode Network, a large network of the human brain, though the underlying neural and cognitive mechanisms remain poorly understood. Here, we tested the hypothesis that our mental experience is mediated by a combination of activities of multiple cognitive processes. Our study included four functional MRI experiments with the same participants and a wide range of cognitive tasks, as well as an analytical approach that afforded the identification of cognitive processes during self-generated cognition. We showed that several cognitive processes functioned simultaneously during self-generated mental activity. The processes had specific and localized neural representations, suggesting that they support different aspects of internal processing. Overall, we demonstrate that internally directed experience may be achieved by pooling over multiple cognitive processes.

Keywords

internally directed cognition; self-generated cognition; internal processing; mind wandering; default mode network; fMRI

Introduction

Self-generated cognition (also referred to as internally directed cognition or internal processing) such as recalling memories, thinking about the future, or just mind wandering, is

Present address of the corresponding author: Dr. Vadim Axelrod, The Gonda Multidisciplinary Brain Research Center, Bar Ilan University, Ramat Gan, 52900, Israel Tel: +972 3 5317755 vadim.axelrod@gmail.com.

Author's contribution:

VA and MB conceived the study. VA designed and performed the study. VA analyzed the data with input from GR and MB. VA, GR and MB wrote the paper.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Code availability

The custom code used in this study is available from the corresponding author upon reasonable request.

Competing interests: Authors declare no competing financial or non-financial interest.

a key part of our experience. The functional roles and benefits of self-generated thinking have not been fully understood¹, but given the abundance of this type of thinking in our lives², self-generated thinking is likely to be essential for humans. Accordingly, understanding the cognitive and neural mechanisms of self-generated cognition is an important endeavor. The literature on self-generated cognition^{3, 4} makes a distinction between self-generated processing that is initiated by an external task (e.g., when a participant is asked to recall some specific past episode^{5–8}) and a spontaneous, unconstrained self-generated processing without a specific task (e.g., mind-wandering^{9–12}). In the present study, we explore task-initiated self-generated processing.

It is generally accepted that the Default Mode Network (DMN) is the principal brain locus of internal processing and self-generated cognition^{4, 13–16}. The DMN has been implicated in various types of processing, such as self-referential processing^{17–23}, mental scene construction^{24–27} and scene imagery²⁸, mental time travel^{29–31}, semantic processing^{32–35}, constructive episodic memory^{5, 6} and retrieval of episodic memory^{36–41}, social-related processing^{42–48}, affective and emotional processing⁴⁹ and creativity^{50, 51}. In addition, functional heterogeneity within the DMN has been established^{52–64}. A conceptualization of these and similar observations has been provided by the multi-component account, according to which the DMN operates through multiple interactive components (or cognitive processes) working together⁴. While the authors of this account do not specify this explicitly, the two important functional principles that stem from the multi-component account are: 1) different cognitive processes work at the same time; and 2) different cognitive processes are responsible for specific and distinct types of processing. Accordingly, to directly and empirically support the multi-component account, both these principles must be shown in action within the same experiment. Previous research on self-generated cognition using both task-based experiments^{7, 8, 21, 65–73} and spontaneous (e.g., resting scan) experiments^{35, 74–81} showed that different parts of the DMN and connectivity between different DMN nodes are selective to different tasks and types of processing. These results have generally supported the multi-component account. Notably, none of the previous studies (except for one, see below) showed different processes working at the same time. In addition, in many task-based studies, the cognitive processes were not identified specifically because this was not the goal of these studies. The only study that satisfied conditions of direct support has been the study of Andrews-Hanna and colleagues⁸², which used a combination of resting state hierarchical clustering, future and present self-related decision tasks, and behavioral introspective measures. The authors showed that the DMN consists of three functionally distinct subsystems that are active at the same time. It is noteworthy that specifically identifying cognitive processes has been traditionally challenging because the cognitive processes are inherently intertwined during self-generated processing. For example, recalling a past episode is likely to entail both episodic memory retrieval and mental scene construction processing, but experimentally to tease these two processes apart is not straightforward^{27, 83}. Additional examples of non-easily dissociated processes include mental time travel and scene construction^{24, 82, 84}, episodic memory retrieval and self-referential processing^{18, 85}, and episodic and semantic memory^{86, 87}. In the present study we devised the approach to address the aforementioned challenges and limitations. This approach permitted us to comprehensively and systematically characterize cognitive

processing within the DMN during self-generated processing, and to test the multi-component proposal directly.

Thirty-six participants took part in four functional MRI (fMRI) experiments (thirty-one of these took part in all four experiment). The experiments included: 1) a main self-generated experiment that included 15-second blocks of free retrieval of personal episodic memory, future and past imagery, and empathizing task; and three experiments that selectively manipulated specific cognitive processes: 2) a self-referential experiment with visually presented verbs that characterize a person; 3) visually presented images of scenes and objects; and 4) visually presented meaningful sentences and non-words (i.e., language-related processing). We predicted that the execution of the self-generated, free tasks in Experiment 1 would be associated with the activity of different cognitive processes. Our approach was to use experiments 2–4 to manipulate specific cognitive processes selectively, and then to use the activity of each of these experiments to identify corresponding cognitive processes during the self-generated processing in Experiment 1. Our goal was to identify and delineate three specific cognitive processes (i.e., self-referential, mental scene construction, and language-related processing) and to show the functioning of these processes at the same time during internal processing, thus supporting the hypothesis that mental experience is mediated by different cognitive processes. It should be emphasized that the goal of the present study was not to determine differences between individual internal tasks; therefore, the comparison of individual tasks was performed only when it served our main goal (see above).

Results

Experiment 1: Self-generated cognition

While lying in the scanner, participants were asked to generate mental experiences associated with a given picture (Fig. 1A; four tasks of interest: imagine what happened before ("past imagery") or after ("future imagery") the depicted scene, recall a personal episodic memory related to the depicted scene ("episodic memory"), imagine yourself as the person in the picture ("empathizing"). The baseline condition was generation of rhymes for a given word. The structure of the trials and visual stimuli were the same for all five conditions, including irrelevant image presentation in the baseline condition to preserve equivalent visual stimulation (see Methods for more details). The four tasks of interest are hereafter referred to as "internal mentation" or "internal" tasks. At the end of each trial, participants provided vividness ratings of their internal experience (Fig. 1a; scale ranged from 1 [highest vividness] to 4 [lowest vividness]). Vividness ratings were as follows: "episodic memory" (mean=1.74, MSE=0.07), "future imagery" (mean=1.74, MSE=0.07), "past imagery" (mean=1.92, MSE=0.07), and "empathizing" (mean=1.77, MSE=0.08). Conditions varied with regard to level of vividness [one-way repeated measures ANOVA: $F(3,105)=3.67, p=0.015, \text{partial } \eta^2=0.095$]. This effect was due to a lower vividness in "past imagery" compared to the other three conditions.

To examine the activity associated with each of the four internal mentation tasks, each task was contrasted separately with the rhyme-generation baseline condition (four separate contrasts; random effects, group-level analysis, primary voxel-wised threshold $p < 0.001$,

$p < 0.05$, cluster size corrected; the primary threshold p -value < 0.001 has previously been shown to control well for the false positive rate (88, 89). The group-level results are shown in Fig. 1b. All four contrasts (i.e., internal tasks) yielded typical DMN activations (13, thus confirming previous reports that different types of internal mental activity engage the DMN (65, 90). As the next step, for key nodes of the DMN network, we extracted percent signal change time-courses. The ROIs (Fig. 1c and Supplementary Table 1) were independently defined (91) based on the individual DMN activation maps obtained in the first session of our experiment; all the analyses presented below were conducted using the remaining sessions (see Methods and Supplementary Methods for more details). The time-courses for all conditions are shown in Fig. 2. First, in all ROIs, we identified a dissociation between the four internal mentation tasks and the baseline rhyme-generation task [average of four internal tasks vs. baseline task: $t(35) > 7.68$, $p < 5 \times 10^{-9}$]. It is worth noting that in both internal and baseline conditions the participants had their eyes closed. Thus, the robust dissociation between two types of conditions underscores that activation of the DMN reflects not merely the absence of an external task, but is also dependent on the nature of the non-external task (e.g., episodic memory thinking vs. rhymes generation). Second, the shape of the internal tasks time-courses differed across DMN regions. In particular, we observed a clear, positive, inverted U-shape response in the posterior cingulate cortex (PCC) and angular gyrus as well as in the medial prefrontal cortex (mPFC) in the "episodic memory" condition. In contrast, there was a negative U-shape response in the parahippocampal cortex (PHC). Dissociation between DMN regions hints at different roles played by different regions in internal processing. It is noteworthy that from the activation maps (Fig. 1b), we could not discern whether the response to the task of interest was activation (e.g., PCC and angular gyrus) or deactivation (e.g., PHC). Finally, in the PCC and mPFC, there were visibly higher responses in "episodic memory" compared to the other conditions. A plausible explanation for this effect is that "episodic memory" (i.e., recalling of personal events) entailed stronger self-related processing compared to other tasks (85). This hypothesis is corroborated by the results in this text (see, Supplementary Figure 2a), but in general, the dissociation between internal tasks is not the focus of the present paper.

We thus established that the DMN was activated by all of the internal tasks of Experiment 1. Now, we proceeded with our main goal – namely, to demonstrate that self-generated processing in the DMN operates through several independent processes.

Experiment 2 – Self-referential processing

We used a commonly accepted method to elucidate self-referential processing by contrasting the activity resulting from making a judgment about the self versus someone else (92–94). In our experiment participants made two types of judgments for the same verbs that describe a person ("self-referential" condition: whether an action was characteristic of them; "non-self-referential" condition: whether an action was characteristic of some ideal person (see Methods for more details). To validate the effectiveness of our manipulation, after the experiment participants rated their subjective experience during the experiment by answering "To what extent each one of the tasks was associated with self-related and personal thoughts?" (Likert scale: 1[low] – 10[high]). The results confirmed that "self-referential" condition was associated with more self-related and personal thoughts than

"non-self-referential" condition ["self-referential": mean=6.03, SEM=0.517; "non-self-referential": mean=4.45, SEM=0.489; paired, two-sided t-test: $t(30)=5.09, p<0.001, \text{Cohen's } d=0.95, \text{CI: } 0.94\text{--}2.21$].

First, we conducted a GLM second-level, random-effect analysis contrasting the "self-referential" versus "non-self-referential" conditions (Fig. 3a). In all figures, the blue contour denotes the DMN identified using first session (independent data). In agreement with previous reports⁹⁴, most of the activations were found in the DMN medial frontal, posterior cingulate, and left lateral posterior parietal regions. This provides evidence, albeit indirect, that during self-generated internal tasks these parts of the DMN are engaged in self-referential processing.

To obtain more direct evidence, we conducted representational similarity analysis⁹⁵ between Experiments 1 and 2. Compared to spatial activation overlap, representational similarity analysis provides stronger evidence because it informs us about the similarity of information processing in brain regions^{96, 97}. For each participant and within each ROI (across voxels), we correlated between contrast values of internal processing selectivity (Experiment 1; contrast: "episodic memory" + "past imagery" + "future imagery" + "empathizing" > "rhymes generation") and contrast values of self-referential selectivity (Experiment 2; contrast: "self-referential" > "non-self-referential"). The results of this analysis are shown in Fig. 3b (for individual data, see Supplementary Figure 1A). Similarity between the two experiments was significantly above zero (after multiple comparison Bonferroni correction for number of tested regions, $N=8, \alpha=0.05/8=0.00625$) in mPFC

[$t(33)=6.37, p<0.001, \text{Cohen's } d=1.09, 99.375\% \text{ confidence interval (CI): } 0.22\text{--}0.61$], PCC [$t(33)=4.75, p<0.001, \text{Cohen's } d=0.81, 99.375\% \text{ CI: } 0.14\text{--}0.57$] and left angular gyrus [$t(33)=3.82, p<0.001, \text{Cohen's } d=0.65, 99.375\% \text{ CI: } 0.07\text{--}0.5$]. In the left LTC, the similarity was above zero, but did not reach significance after multiple comparison [$t(33)=2.83, p=0.0078, \text{Cohen's } d=0.49, 99.375\% \text{ CI: } -0.004\text{--}0.3$]. In the remaining regions, the similarity did not differ from zero [$t<1$]. To examine the specificity of the result, we conducted two types of analyses. First, we tested regional specificity by comparing the similarity between regions. For the mPFC and PCC, the similarity was significantly higher (after multiple comparison Bonferroni correction for number of tested regions, $N=7, \alpha=0.05/7=0.0071$) than in the right angular gyrus, bilateral LTC, and bilateral PHC ($p<0.001, \text{Cohen's } d > 0.6$). For the left angular gyrus, the similarity was significantly higher than in the right angular gyrus, right LTC, and bilateral PHC ($p<0.001, \text{Cohen's } d > 0.71$), but did not significantly differ from the left LTC after multiple comparison correction ($p=0.021, \text{Cohen's } d>0.42$). No significant difference in similarity was observed between the mPFC, PCC, and left angular gyrus ($p>0.1$). Second, we tested processing type specificity by comparing the similarity obtained in the present analysis [i.e., similarity between internal processing (Experiment 1) and self-referential processing (Experiment 2)] versus the similarity of internal processing (Experiment 1) and each of two additional experiments presented below (Experiment 3: scene construction and Experiment 4: language-related processing; see Supplementary Methods for more details). Compared to internal processing vs. scene construction, we found high specificity in mPFC [$t(31)=5.5, p<0.001, \text{Cohen's } d=1$], PCC [$t(31)=4.96, p<0.001, \text{Cohen's } d=0.92, 99.375\% \text{ CI: } 0.35\text{--}0.76$], and the left angular gyrus [$t(31)=4.26, p<0.001, \text{Cohen's } d=0.75, 99.375\% \text{ CI: } 0.17\text{--}0.86$]. Compared to internal

processing vs. language-related processing, there was high self-referential specificity in the mPFC [$t(31)=3.89, p<0.001, \text{Cohen's } d=0.69, 99.375\% \text{ CI: } 0.11-0.82$] and PCC [$t(31)=2.87, p=0.007, \text{Cohen's } d=0.51, 99.375\% \text{ CI: } -0.001-0.6$], but not in the left angular gyrus [$t(31)<1$].

In addition to ROI analysis, we conducted a searchlight representational analysis between internal processing (Experiment 1) and self-referential selectivity (Experiment 2). The main benefit of this approach is that this analysis makes no a priori assumptions regarding ROI location, thus permitting the examination of similarity across different parts of the DMN, as well as outside the DMN. The unthresholded findings are shown in Fig. 3c (top) and the significant clusters in Fig. 3c (bottom; primary voxel-wised threshold $p<0.001, p<0.05$, cluster size corrected). Remarkably, in line with ROI analysis, the only three significant clusters were in the mPFC, PCC, and left angular gyrus (Supplementary Table 2). We can clearly see that no significant representational similarity was identified (at the statistical thresholds used) in LTC, PHC, right angular gyrus DMN regions or any outside-DMN regions. Taken together, we conclude that mPFC, PCC and left angular gyrus were the primary loci of self-referential processing during internal processing of Experiment 1.

In previous analyses, the four internal tasks were considered as one condition (i.e., "internal processing"). As a complementary and more exploratory analysis, we conducted representational similarity analysis between individual internal tasks of Experiment 1 and Experiment 2 (for full results, see Supplementary Results, "Representational ROI analysis of individual tasks"). In the mPFC and PCC, across four tasks of Experiment 1 the highest similarity was observed between the "episodic memory" task and the self-referential processing of Experiment 2 (Supplementary Figure 2a). This result corroborates the idea that higher BOLD signals associated with "episodic memory" in mPFC and PCC of Experiment 1 (Fig. 2) was at least partially related to self-referential processing.

In a complementary analysis, we also tested similarities between self-referential and language-related processing (Experiment 3), as well as the similarity between self-referential and scene-construction processing (Experiment 4). Results of these analyses are presented in the Supplementary Results and Supplementary Figs. 3 and 4. We found clusters with a high similarity between self-referential and language-related processing in the lateral temporal and frontal cortex, but mostly not within the DMN (Supplementary Figure 4).

Experiment 3 – Scene construction

Results of Experiments 1 and 2 reveal an interesting dissociation with regard to the PHC: whereas the region exhibited a much higher response to internal tasks compared to baseline in Experiment 1 (Figs. 1b and 2), it was not involved in self-referential processing in Experiment 2 (Fig. 3). In general, the PHC has primarily been implicated in spatial navigation, visual scene processing, and contextual processing⁹⁸. In addition, it has been suggested that the region plays a role in scene construction during internal mentation^{24–27}, as well as in imagery²⁸. To test whether the scene construction hypothesis can explain the dissociation between Experiments 1 and 2 with regard to PHC, after the study we asked participants to rate the extent each of the tasks was associated with having a mental scene in their minds (Likert scale: 1[low] – 10[high]). We found that in Experiment 1, the subjective

experience of "a scene in the mind" was much stronger during the internal tasks than during the rhymes generation task [internal tasks: mean=7.74, SEM=0.33; rhymes generation: mean=1.52, SEM=0.21; $t(32)=19.33, p<0.001, \text{Cohen's } d=3.36, \text{CI: } 5.57\text{--}6.88$]. In contrast, in Experiment 2 there was only a slight and insignificant difference in the subjective experience of "a scene in the mind" between "self-referential" and "non-self-referential" conditions ["self-referential": mean=3.16, SEM=0.43; "non-self-referential": mean=2.8, SEM=0.44; $t(30)<1, \text{Cohen's } d=0.17, \text{CI: } -0.39\text{--}1.09$]. Thus, the role of the PHC during internal processing (i.e., Experiment 1) may indeed be related to mental scene construction. To investigate this question more directly, we conducted additional fMRI experiment with the same participants. Experiment 3 included visual presentation of unfamiliar images of scenes and objects⁹⁹. The key idea was to use the scene-selective activity of Experiment 3 as the neural marker to find mental scene construction during self-generated tasks of Experiment 1.

First, we conducted a GLM second-level, random-effect analysis contrasting "scenes" versus "objects" conditions (Fig. 4a). This revealed a well-characterized network of scene-selective regions in the PHC, retrosplenial cortex and middle occipital gyrus (also referred as transverse occipital sulcus)¹⁰⁰. Large parts of this network overlapped with the DMN (particularly the PHC), but there were also parts of the network identified outside the DMN (in line with recent report¹⁰¹). Thus, the fact that the same neural substrates were active in both Experiments 1 and 3 supports, albeit indirectly, the idea that scene construction processes may play a role during internal processing in Experiment 1.

Next, using the same independent ROIs defined in Experiment 1, we conducted representational similarity analysis between internal processing in Experiment 1 and scene construction in Experiment 3. The results are shown in Fig. 4b (for individual data, see Supplementary Figure 1b). We found that the only two regions showed strong and highly significant positive similarity (after multiple comparison Bonferroni correction for number of regions) were the left PHC [$t(32)=6.74, p<0.001, \text{Cohen's } d=1.17, 99.375\% \text{ CI: } 0.14\text{--}0.37$] and right PHC [$t(32)=7.09, p<0.001, \text{Cohen's } d=1.23, 99.375\% \text{ CI: } 0.15\text{--}0.36$]. In all remaining regions, the similarity was negative. This result was close to significance (after multiple comparison correction) only in the PCC [$t(32)=-2.92, p=0.0062, \text{Cohen's } d=0.51, 99.375\% \text{ CI: } -0.45\text{--}0$], but not in other regions ($p>0.01, \text{Cohen's } d<0.47$). Examination of a direct regional specificity revealed that similarity in the bilateral PHC was significantly higher (after multiple comparison correction) than in all other regions [$t(32)>4.01, p<0.001, \text{Cohen's } d>0.89$]. Examination of processing type specificity revealed high specificity in the bilateral PHC relative to internal processing vs. self-referential processing [left PHC: $t(31)=5.06, p<0.001, \text{Cohen's } d=0.89, 99.375\% \text{ CI: } 0.16\text{--}0.51$; right PHC: $t(31)=5.5, p<0.001, \text{Cohen's } d=0.97, 99.375\% \text{ CI: } 0.16\text{--}0.47$]. Relative to internal processing vs. sentence-related processing, we found high specificity in the right PHC [$t(31)=4.16, p<0.001, \text{Cohen's } d=0.74, 99.375\% \text{ CI: } 0.07\text{--}0.39$] and moderate specificity in the left PHC [$t(31)=2.41, p=0.022, \text{Cohen's } d=0.43, 99.375\% \text{ CI: } -0.03\text{--}0.3$].

In addition, we conducted a searchlight representational analysis between internal processing (Experiment 1) and scene construction (Experiment 3). The results are shown in Fig. 4c. In line with ROI analysis, the highest similarity was found in the bilateral PHC (Supplementary Table 2). In addition, we found relatively high levels of similarity in the

retrosplenial cortex and middle occipital gyrus. In line with ROI representational analysis, we can see strong negative similarity (light blue color) in the medial frontal and posterior cortex, as well as in the left posterior parietal DMN regions (Fig. 4c, top). Taken together and in agreement with the literature on scene construction^{24–27}, we conclude that: a) scene construction process is likely playing an active role during internal mentation processing; b) the PHC, and to a lesser extent parts of the retrosplenial cortex and middle occipital gyrus, are the loci of scene construction processing during internal mentation.

As in Experiment 2, we also conducted exploratory representational similarity analysis in the PHC between the individual internal tasks of Experiment 1 and Experiment 3 (see Supplementary Results, "Representational ROI analysis of individual tasks"). The similarity level across individual internal tasks was mostly similar, with a slight trend to lower similarity in the "empathizing" task.

Experiment 4 – Language-related processing

Language processing activates a large extent of the lateral parieto-temporal and frontal lobes^{102, 103}. The language network partially overlaps with the DMN (i.e., LTC and lateral posterior cortex regions), although specifically in the domain of language research, this observation has drawn relatively little attention^{102, 104–106}, but see refs^{107, 108}. In addition, there is a broad concept of semantic processing, which is explored both as part of the language system¹⁰⁹ and as an independent domain (e.g., conceptual knowledge¹¹⁰, semantic information about a face^{111, 112}). Following the seminal work of Binder and colleagues, the role of semantics in DMN processing is widely acknowledged³². While early work tended to suggest the involvement of the whole DMN in semantic processing^{32, 113}, more recent studies have emphasized the role of more specific DMN nodes such as LTC and lateral posterior cortex^{33, 34, 114} and to a lesser extent the PCC¹¹⁵. We used our general approach described above to identify language-related processing during internal processing (i.e., the internal tasks of Experiment 1). The same participants of Experiments 1–3 took part in Experiment 4, which used a well-established paradigm to identify language-related processing¹⁰³. Participants were visually presented meaningful sentences and series of meaningless non-words, while the words or non-words were presented one item at a time (see Methods for full details).

First, we conducted a GLM second-level, random-effects analysis contrasting meaningful sentences and meaningless non-words conditions (Fig. 5a). We observed a well-known network of regions related to language processing¹⁰³. We can also clearly see that the bilateral LTC and to smaller extent lateral posterior cortex regions overlap with the DMN. Next, using independent ROIs from Experiment 1, we conducted representational similarity analysis between internal processing in Experiment 1 (four internal tasks > baseline) and language-related processing in Experiment 4 (meaningful sentences > meaningless non-words). This analysis revealed (Fig. 5b and Supplementary Figure 1c, for individual data) strongest and highly significant similarity (after multiple comparison Bonferroni correction) in the bilateral LTC [left LTC: $t(33)=8.22, p<0.001, \text{Cohen's } d=1.41, 99.375\% \text{ CI: } 0.25\text{--}0.53$; right LTC: $t(33)=9.9, p<0.001, \text{Cohen's } d=1.7, 99.375\% \text{ CI: } 0.29\text{--}0.53$]. In addition, a much weaker, but still significant (after multiple comparison Bonferroni correction), the similarity

was found in the right angular gyrus ($t(33)=3.04, p=0.005$, Cohen's $d=0.52$, 99.375% CI: 0.01–0.39). In the remaining regions the similarity values were not significant: left PHC [$t(33)=2.58, p=0.014$, Cohen's $d=0.44$, 99.375% CI: -0.01–0.23], left angular gyrus [$t(33)=2.33, p=0.026$, Cohen's $d=0.4$, 99.375% CI: -0.05–0.41], PCC, mPFC, and right PHC [$t(33)<1$]. Examination of direct regional specificity revealed that similarity in the bilateral LTC was significantly higher (after multiple comparison correction) than in the PCC, mPFC and bilateral PHC [$t(33)>5.4, p<0.001$, Cohen's $d>0.93$]. The right LTC had significantly higher similarity (after multiple comparison correction), compared to the bilateral angular gyrus [$t(33)>3.15, p<0.003$, Cohen's $d>0.54$]. The left LTC had significantly higher similarity (after multiple comparison correction), compared to the left angular gyrus [$t(33)=3.15, p=0.003$, Cohen's $d=0.54$, 99.28% CI: 0.02–0.4], but compared to the right angular gyrus the results did not reach significance after multiple comparison [$t(33)=2.68, p=0.01$, Cohen's $d=0.46$, 99.28% CI: -0.01–0.4]. Similarity in the right angular gyrus was significantly higher (after multiple comparison correction), only compared to the mPFC [$t(33)=4.05, p<0.001$, Cohen's $d=0.69$, 99.28% CI: 0.1–0.56]. Examination of processing type specificity revealed that the bilateral LTC was highly specific relative to both internal processing vs. self-referential processing [left LTC: $t(31)=4.55, p<0.001$, Cohen's $d=0.8$, 99.375% CI: 0.09–0.43; right LTC: $t(31)=6.47, p<0.001$, Cohen's $d=1.14$, 99.375% CI: 0.22–0.57] and internal processing vs. scene construction [left LTC: $t(31)=7, p<0.001$, Cohen's $d=1.23$, 99.375% CI: 0.24–0.58; right LTC: $t(31)=8.15, p<0.001$, Cohen's $d=1.44$, 99.375% CI: 0.31–0.66].

In addition, we conducted a searchlight representational analysis between internal processing (Experiment 1) and scene construction (Experiment 4). The unthresholded findings and significant clusters are shown in Fig. 5c (top) and Fig. 5c (bottom; primary voxel-wised threshold $p<0.001, p<0.05$, cluster size corrected), respectively. In agreement with ROI analysis, the highest similarity has been found in the bilateral LTC. The similarity was found to a much lesser extent in the lateral posterior parietal regions, while only the cluster in the right hemisphere reached significance. An additional small cluster has been also found in the right superior frontal gyrus (see, Supplementary Table 2). In total, we conclude that a) language-related processing plays a role during internal mentation processing; b) the bilateral LTC, and to a much lesser extent the lateral posterior parietal region, are the loci of language-related processing during internal mentation

We also conducted an exploratory representational similarity analysis between individual internal tasks of Experiment 1 and Experiment 4. We found that similarity during episodic memory task was lower, particularly in the left LTC, compared to other tasks (see Supplementary Results, "Representational ROI analysis of individual tasks").

To summarize the key results, significant clusters from the searchlight representational similarity analyses were converted into binary maps. The neural substrates of three cognitive processes identified are shown in Fig. 6.

Discussion

In the present study, using four fMRI experiments with the same participants we delineated the neural substrates of three cognitive processes and showed that these neural substrates were active concurrently during self-generated cognition. These findings support the idea that our internal mental experience is the result of a combination of activities from different cognitive (and neural) processes.

The DMN is one of the most explored networks of the human brain¹⁴. This network specializes in the amodal, non-sensory, internally directed cognition and is located at the apex of the processing hierarchy⁴⁰, 116–118. According to an influential multi-component account⁴, internal experience is a combination of activity of different cognitive processes operating within the DMN. Through a series of analyses, we identified the neural substrates of three cognitive processes: self-referential processing, mental scene construction, and language-related processing (Fig. 6). Our study was designed a priori to focus on these cognitive processes, so our results do not imply that these three processes were the only active processes during internal processing tasks. In order to specifically delineate cognitive processes during self-generated processing, we used an experimental approach that included separate experiments to elucidate a specific type of processing (i.e., Experiments 2–4) followed by representational similarity analysis between experiments (see further discussion below). We showed that different cognitive processes all functioned at the same time during self-generated processing (i.e., internal tasks of Experiment 1). Put simply, the participants were lying in a scanner with their eyes closed, performing the internal tasks of Experiment 1. With the help of Experiments 2–4 and especially the use of representational similarity analysis, we established that the mental experience of the participants was a mixture of self-referential, mental scene construction, and language-related cognitive processes. We observed that: a) different cognitive processes have specific neural representations, both at the level of regional specificity and at the level of processing type specificity; and b) the activity level of the cognitive system could differ across tasks, possibly reflecting the extent to which the process is needed for execution of a specific task (e.g., higher activity of self-referential system while recalling a personal event compared to imagining non-personal situation, Supplementary Figure 2a). Our neuroimaging results were paralleled by introspective behavioral reports, showing that participants had vivid scenes in their minds while performing the tasks of Experiment 1, but not during the self-referential processing of Experiment 2. All this suggests that different processes are likely responsible for different aspects of internal processing. Taken together, our results support the idea that our mental experience is mediated by different cognitive processes.

Self-generated cognition in the DMN has been explored extensively, especially over the last decade. Task-based self-generated studies have revealed that while the DMN is involved in processing various self-generated tasks^{15, 90, 119}, the network is also heterogeneous in such a way that different parts of the DMN are selective to specific tasks and types of processing^{7, 8, 18, 65–69, 120, 121}. For example, both autobiographical memory and theory of mind tasks activate the frontal and temporal-parietal regions, but the autobiographical memory task activates the midline regions more strongly⁷. The observation that different parts of the DMN are selective to specific tasks supports the multi-component account, but

this support is only indirect. First, contrasting between cognitively complex internal tasks (e.g., recalling personal episode vs. empathize with someone), as was done in many previous studies, is unlikely to delineate cognitive processes in a specific way because such tasks are different in many aspects. Second, and even more critical, none of the previous studies (except for one, see below) demonstrated several cognitive processes working at the same time. In fact, it does not seem even theoretically possible to show several processes working at the same time when a contrast between two tasks is the analysis method. Another corpus of studies explored spontaneous (i.e., non-task initiated) self-generated cognition in the DMN by correlating across participants functional^{35, 74–81} (or anatomical⁷⁴) connectivity during resting scan with behavioral measures obtained outside the scanner. The researchers found, for example, that specific connectivity patterns in the DMN were associated with behavioral mind-wandering scores⁷⁹, that patterns of hippocampus connectivity were associated with individual autobiographical goals⁸⁰, and that connectivity between PCC and the temporal lobe was associated with different features of experience such as episodic memory and emotions⁷⁵. Overall, the aforementioned resting-state studies revealed the component processes and components of thought, thus supporting the multi-component account. However, given that the functional connectivity measures are based on several minutes of resting scans, and the fact that correlation analyses are conducted across participants, the results of these studies do not directly support the thesis that the specific cognitive experience of an individual person is achieved by several cognitive processes working at the same time. It is noteworthy that some of the previous studies identified components of thought (or types of thought), but not cognitive processes^{75–78}. But it is not evident how components of thought such as "thinking about the future" or "being on task" are mapped onto cognitive processes. Overall, while many studies have supported the multi-component account, more direct support is still needed.

To date, the study by Andrews-Hanna and colleagues⁸² has been the only study that provided direct support to the multi-component account, by showing that different cognitive processes work concurrently. A follow-up study of Andrews-Hanna and colleagues⁷⁰ also demonstrated different cognitive processes, but without showing them working together. Compared to the first study of Andrews-Hanna and colleagues⁸², here we report one largely similar cognitive process (i.e., self-related processing), another more specific and restricted cognitive process (i.e., current "mental scene construction" vs. previously reported "mental scene construction and episodic memory"), and also an additional cognitive process (language-related processing; see more detailed discussion below). We also extend previous findings by showing that cognitive processes might have variable levels of activity across different tasks (Supplementary Figure 2). Finally, to identify cognitive processes in the brain, our method does not rely on introspective reports. That is, whereas introspective experience sampling is a valuable tool^{5, 11, 75, 76, 82}, its general limitation is that participants can report only on matters of which they were aware. For example, in our case, it would have been very difficult – if not impossible – to obtain a reliable report of the extent to which participants used language-related or semantic systems during recall of a past episode from memory. Using our method, it was possible to identify cognitive systems that operate largely unconsciously.

The cognitive systems we identified were mostly confined to the DMN (Fig. 6), corroborating the principal role of the DMN in self-generated cognition. More specifically, self-referential processing was found in the PCC and medial PFC, which is in agreement with the large self-referential literature^{17, 18, 20, 21, 23} and self-related component reported earlier⁸². In addition, again in line with the literature⁹⁴, the self-referential processing system included the lateral parietal cortex region (mostly angular gyrus) with a strong left lateralization (Figs. 3 and 6). The effect of laterality that we found underscores that when the analysis of the DMN is conducted for only one hemisphere [e.g. ref 82], caution is needed when these results are generalized to another hemisphere. The mental scene-construction cognitive system that we identified exhibited a large locus in the PHC and weaker activity in the retrosplenial and middle occipital cortex (Figs. 4 and 6). These results are in agreement with previous reports, implicating these regions in scene imagery²⁸ and mental scene construction^{24–27}. Some of the brain regions associated with mental scene construction were not only inside, but also outside the DMN (Fig. 6). This observation is reminiscent of a recent proposal¹⁰¹, according to which the scene processing system consists of two networks: the first being perceptual-visual (i.e., outside DMN) and the second one being non-perceptual, which is related to various types of internal processing (i.e., within DMN). A final note relates to the methodology that we used. The use of perceptual task (i.e., visual scenes) as a biomarker to identify mental scene construction was based on a wealth of evidence that there is neural similarity between visual imagery and perception^{122–124}. However, despite this similarity, perception and imagery are still different phenomena. In particular, the fact that the extent of our scene construction component was relatively limited in the DMN could potentially result from using a perceptual task as a biomarker. In the future, it will be of interest to validate our results using a non-perceptual task as a biomarker to identify mental scene construction process.

We also successfully delineated language-related processing within the DMN, demonstrating that language-related processing plays a prominent role during internally directed cognition. The loci of language-related activity were very specific: the strongest in the lateral temporal cortex and to a much lesser extent in the lateral posterior parietal cortex (Figs. 5 and 6). These results agree with previous results regarding the role of these regions in semantic processing^{32–34}. Notably, our evidence was based on representation analysis, which is a much stronger measure for establishing processing similarities compared to the conjunction analysis (i.e., spatial overlap of activations) used previously^{32, 34}. We found some level of right lateralization in the lateral posterior parietal cortex (Fig. 5c), though it did not reach significance in a direct test. Interestingly, a very significant opposite (i.e., left) lateralization effect was found for self-referential processing (Fig. 3c). Thus, we may observe hemispheric functional specialization at the level of different cognitive processes. It is worth noting that our study did not attempt to elucidate specific types of language-related processing (e.g., syntax, inner speech, semantics). In the future, by capitalizing on our approach and methodology, it may be possible to subdivide language-related processing into smaller processes.

An essential aspect of the present work is that we have identified the specific neural substrates of cognitive processes. Delineating specific processes during self-generated processing has traditionally been challenging due to the processes being inherently

intertwined. For example, functional profiles of episodic memory retrieval and self-referential processing^{18, 85}, episodic and semantic memory^{86, 87}, as well as episodic memory and mental scene construction^{27, 83} are not easily dissociated. To some extent, inaccurate delineation of neural loci of cognitive processes could have potentially contributed to the proposals that there is only one key cognitive process within the DMN^{19, 26, 32, 125}. That is, these studies could have attributed a mixture of cognitive processes to a single process. Herein, we ensured specific delineation by selectivity manipulating a specific type of processing in Experiments 2–4. The neural signature obtained in these experiments was compared to the self-generated internal processing observed in Experiment 1. Critically, we found a neural similarity between Experiment 1 and Experiments 2–4, despite the use of completely different designs, stimuli, and tasks, therefore suggesting that we are dealing with a genuine phenomenon. Furthermore, we used representational similarity analysis⁹⁵ – an approach that helps establish similarity in information processing⁹⁶. Remarkably, the high similarity we found was in very specific regions and observed through comparison of very specific experiments. This latter observation speaks against the possibility that the correlation reflects some unspecific, cognitively unrelated phenomenon (e.g., vascular response). Overall, our experimental approach permitted to achieve a specific and accurate delineation of cognitive processes. We suggest that our approach can be used in the future to explore additional cognitive systems. In particular, DMN processing in general and specifically the internal tasks used here are to a large extent social in nature^{19, 42, 70, 126}. Using our design, we could not estimate and evaluate what role social processing played in the execution of the self-generated tasks of Experiment 1. In the future, using the approach proposed here, it should be possible to identify cognitive processes related to social cognition and theory of mind.

In conclusion, the key finding of the present work was that several distinct cognitive processes are active concurrently during internal processing. This result supports the idea that human cognitive experiences may be achieved by pooling over multiple cognitive processes at any given time.

Methods

Apparatus

MRI data were collected using a 3T GE MRI scanner. The key functional MRI EPI parameters were: TR: 2.5 sec; TE: 30 ms; slice thickness: 3.6 mm; in-plane acquisition resolution: 2.08x2.08 mm. For more details, see Supplementary Methods.

Participants

Forty-one healthy volunteers: average age: 28 (standard deviation: 5.07), 17 females, two left-handed. The study was approved by the ethics committee of the Tel Aviv Sourasky Medical Center. Informed written consent was provided by all participants before starting the experiment. Data of five participants were excluded from the analysis due to excessive movements in the scanner (>1 cm). The number of participants reported below is after exclusion of these five participants. The number of participants in each experiment was as follows: Experiment 1: thirty-six, Experiment 2: thirty-four, Experiment 3: thirty-three,

Experiment 4: thirty-four. Thirty-one participants took part in all experiments. Our sample size was above the current median number of participants in fMRI studies¹²⁷ and approximately double the number of participants in key studies in this field^{5, 25, 65, 69, 93}. In addition to the listed experiments, the study included resting state session (duration: 6 minutes and 10 seconds). The resting state session was not analyzed in the present paper.

Experimental Setup

Experiment 1 – Self-generated cognition—Images of real-life situations were used in the experiment. Participants performed five tasks, defined by an image cue and task instruction (Fig. 1a). Four internal mentation tasks were as follows: (1) "past imagery": imagining the situation that had happened before the depicted scene; (2) "future imagery": imagining the situation that might happen after the depicted scene; (3) "episodic memory": recalling a personal episodic memory event related to the depicted scene; (4) "empathizing": imagining yourself in the place of the person in the image. Baseline condition ("rhyme generation") required generation of the words that rhyme with a given word (unrelated to a stimulus image). The structure of the trials is presented in Fig. 1a and it was identical for all conditions. All the tasks were executed silently ("in the mind"), without speech. For more details, see Supplementary Methods.

Experiment 2 – Self-referential processing—The material included 54 single Hebrew verbs words (infinitive verbs), which can characterize a person (e.g., to volunteer, to smile, to lie, to smoke). The design of these experiments was similar to previous experiments with self-referential tasks^{92–94}. The two key conditions of our experiment were: 1) "self-processing" condition: to decide whether the action described by a verb was characteristic or not of a participant; 2) "non-self-processing" condition: to decide whether an action was characteristic of some ideal person. For more details see the Supplementary Methods.

Experiment 3 – Visual scenes and objects—We used a standard visual functional localizer of scene-selective regions⁹⁹, which included images of unfamiliar natural scenes (e.g., mountains, lakes) and everyday objects (e.g., a ball, a chair). The behavioral task was "1-back" (i.e., to detect the same image that appeared twice in a row). The design was very similar to the one used in our previous study¹²⁸. For more details see the Supplementary Methods.

Experiment 4 – Language-related processing—The paradigm we used has been shown to reliably localize the language-processing network¹⁰³. The design described below is almost identical to the one used in our previous studies^{129, 130}. The words (non-words) were presented sequentially at fixation. There were two conditions: the written meaningful sentences (comprised of words), and the series of meaningless non-words. Non-words were created as random permutation of the letters, so most of the non-words were unpronounceable and could not be read. The number of letters in the words and non-words was the same. For more details, see Supplementary Methods.

Behavioral assessment outside the scanner—After completing all fMRI experiments, participants rated their subjective experiences during scanning [Likert scale: 1

(low level)–10 (high level)]. For establishing the extent participants were engaged in self-referential processing during the tasks of Experiment 2, we asked them "To what extent each one of the tasks was associated with self-related and personal thoughts?". To evaluate mental scene imagery during the execution of tasks in Experiments 1 and 2, the participants were asked: "To what extent each one of the tasks was associated with having a mental scene in your mind?" Due to technical problems, behavioral reports for three participants are missing.

Data Analysis

Preprocessing—SPM5 (Wellcome Trust Centre for Neuroimaging, London, UK; <http://www.fil.ion.ucl.ac.uk>) was used for data analysis. The preprocessing steps included realignment, slice-time correction, motion correction, normalization (2x2x3 mm voxel size) and spatial smoothing (FWHM = 6 mm kernel). A unified segmentation procedure¹³¹ was used for normalization. Representational similarity analysis was conducted using non-smoothed data.

Experiment 1 – Self-generated cognition—The data from the experiment were split into two parts: the first session and the remaining sessions. The first session was used for defining Regions of Interest (see below) and for illustration of the DMN as a blue contour (Figs. 3–6). The remaining sessions were used for all the main analyses. This procedure ensured independent ROI localization⁹¹.

The first-level fixed effects GLM model (boxcar function) was estimated using five regressors of interest: "future imagery", "past imagery", "episodic memory", "empathizing", and "rhyme generation". Six motion parameters from preprocessing step were included as the covariate of no interest. The task analysis period was 15 sec (task instruction: 4 s and the period after instruction: 11 s). Control analysis for only the period after instruction (11 s) yielded qualitatively similar results. For each internal task, we defined first-level contrast as internal task larger than "rhyme generation" (4 separate contrasts). Four second-level random effects group models were estimated using first-level contrasts. The resulting activation maps were thresholded with a voxel-wise primary threshold p -value < 0.001 and cluster-level threshold p -value < 0.05, corrected. The primary threshold p -value < 0.001 has been previously shown to control well for the false positive rate^{88, 89}. The cluster-level thresholding was done using Monte-Carlo simulation using the AlphaSim function in a REST toolbox¹³². This thresholding approach is widely used in the fMRI literature (e.g. refs^{133–135}). Percent signal change time-courses (Fig. 2) were extracted using the MarsBar region of interest toolbox for SPM¹³⁶.

ROIs were defined individually for each participant as the cluster with the highest DMN selectivity in the first session. ROIs were created automatically (MATLAB custom code¹³⁷) based on the individual DMN peak activations constrained by the parcellation atlas of Craddock and colleagues¹³⁸. For full details see Supplementary Methods, ROI definition. ROI volume was 2160 mm³, approximately equivalent to a sphere with radius 8 mm. Average location of the ROIs is shown in Fig. 1c and Supplementary Table 1.

Representational similarity analyses (RSA)^{95, 139} were performed using spatially non-smoothed data. We explain the similarity analysis between Experiment 1 (internal

processing) and Experiment 2 (self-referential processing). Other similarity analyses were conducted using the same logic. In the ROI RSA, for each participant/ROI, the first-level analysis contrast values (i.e., SPM "con" images) of Experiment 1 (four internal tasks > rhymes generation contrast) and Experiment 3 ("self-referential" vs. "non-self-referential") were extracted. Thus, for each region, we obtained two vectors of data (i.e., one vector per contrast). We calculated the Spearman rank correlation between these vectors. Similar results were obtained using Pearson and Kendall tau. Correlation values were subsequently transformed using Fischer r-to-z transform. For each region, transformed correlation values across participants were submitted to one-sample, two-sided t-test vs. 0. Prior to this, normality assumptions were validated using the Lilliefors test. Similarity values significantly above zero indicate that there was some degree of similarity between the two types of processing. Bonferroni multiple comparison correction for number of regions was used (number of regions=8, $\alpha=0.05/8=0.00625$). To establish regional specificity, we compared similarity values with values of other ROIs. Bonferroni multiple comparison correction for the number of comparison of each ROI was used (number of comparisons=7, $\alpha=0.05/7=0.0071$). We also conducted processing type specificity analysis (see the corresponding section in the Supplementary Methods). In the whole-brain searchlight RSA139, 140, we used a sphere with a radius 4 mm (268 mm³). Results with a larger sphere (radius: 8 mm, volume: 2145 mm³) were generally similar, but a smaller sphere improved spatial specificity. Iteratively, the sphere was moved with a step of one voxel over the whole brain, so that each time a different voxel was used as a centre of a sphere112. At the end of the process, the similarity values for each voxel were averaged141. Significance was established at group level (i.e., across subjects) using one-sample, two-sided t-test vs. 0. The resulting activation maps were thresholded using exactly the same procedure used in the GLM analysis: voxel-wise primary threshold p -value < 0.001 and cluster-level threshold p -value < 0.05, corrected (cluster size was established using Monte-Carlo simulation132). In addition, the unthresholded statistical maps were also shown (Figs. 3c, 4c and 5c).

Experiment 2 – Self-referential processing—The first-level GLM model (boxcar function) was estimated for each participant using three regressors of interest (i.e., self-processing, non-self-processing and letters comparison) and six motion parameters as regressors of no interest. To assess self-referential selectivity, the SPM contrast "self-processing" greater than "non-self-processing" was used.

Experiment 3 – Visual scenes and objects—The first-level GLM model (boxcar function) was estimated for each participant using two regressors of interest (scenes and objects conditions) and six motion parameters as regressors of no interest.

Experiment 4 – Language-related processing—The first-level GLM model (boxcar function) was estimated for each participant using two regressors of interest (meaningful sentences and non-words) and six motion parameters as regressors of no interest.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This work was supported by the Yad HaNadiv Rothschild fellowship (VA), the Wellcome Trust (GR) and the Israeli Center of Research Excellence in Cognitive Sciences (MB). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. We also thank Katarzyna Siuda-Krzywicka and Samuel Schwarzkopf for advice and Noy Hale for technical assistance.

References

- 1 Smallwood J, Schooler JW. The Science of Mind Wandering: Empirically Navigating the Stream of Consciousness. *Annu Rev Psychol.* 2015; 66:487–518. [PubMed: 25293689]
- 2 Killingsworth MA, Gilbert DT. A Wandering Mind Is an Unhappy Mind. *Science.* 2010; 330:932. [PubMed: 21071660]
- 3 Smallwood J. Distinguishing how from why the mind wanders: a process–occurrence framework for self-generated mental activity. *Psychol Bull.* 2013; 139:519. [PubMed: 23607430]
- 4 Andrews-Hanna JR, Smallwood J, Spreng RN. The default network and self-generated thought: component processes, dynamic control, and clinical relevance. *Ann N Y Acad Sci.* 2014; 1316:29–52. [PubMed: 24502540]
- 5 Addis DR, Wong AT, Schacter DL. Remembering the past and imagining the future: Common and distinct neural substrates during event construction and elaboration. *Neuropsychologia.* 2007; 45:1363–1377. [PubMed: 17126370]
- 6 Addis DR, Pan L, Vu M-A, Laiser N, Schacter DL. Constructive episodic simulation of the future and the past: Distinct subsystems of a core brain network mediate imagining and remembering. *Neuropsychologia.* 2009; 47:2222–2238. [PubMed: 19041331]
- 7 Rabin JS, Gilboa A, Stuss DT, Mar RA, Rosenbaum RS. Common and unique neural correlates of autobiographical memory and theory of mind. *J Cogn Neurosci.* 2010; 22:1095–1111. [PubMed: 19803685]
- 8 Rabin JS, Rosenbaum RS. Familiarity modulates the functional relationship between theory of mind and autobiographical memory. *Neuroimage.* 2012; 62:520–529. [PubMed: 22584225]
- 9 Axelrod V, Rees G, Lavidor M, Bar M. Increasing propensity to mind wander with transcranial direct current stimulation. *Proc Natl Acad Sci.* 2015; 112:3314–3319. [PubMed: 25691738]
- 10 Christoff K, Gordon AM, Smallwood J, Smith R, Schooler JW. Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proc Natl Acad Sci.* 2009; 106:8719–8724. [PubMed: 19433790]
- 11 Stawarczyk D, Majerus S, Maquet P, D'Argembeau A. Neural correlates of ongoing conscious experience: both task-unrelatedness and stimulus-independence are related to default network activity. *PLoS One.* 2011; 6:e16997. [PubMed: 21347270]
- 12 Smallwood J, Schooler JW. The restless mind. *Psychol Bull.* 2006; 132:946. [PubMed: 17073528]
- 13 Buckner RL, Andrews-Hanna JR, Schacter DL. The Brain's Default Network. *Ann N Y Acad Sci.* 2008; 1124:1–38. [PubMed: 18400922]
- 14 Raichle ME. The brain's default mode network. *Annu Rev Neurosci.* 2015; 38:433–447. [PubMed: 25938726]
- 15 Stawarczyk D, D'Argembeau A. Neural correlates of personal goal processing during episodic future thinking and mind-wandering: An ALE meta-analysis. *Hum Brain Mapp.* 2015; 36:2928–2947. [PubMed: 25931002]
- 16 Fox KC, Spreng RN, Ellamil M, Andrews-Hanna JR, Christoff K. The wandering brain: Meta-analysis of functional neuroimaging studies of mind-wandering and related spontaneous thought processes. *Neuroimage.* 2015; 111:611–621. [PubMed: 25725466]
- 17 Northoff G, et al. Self-referential processing in our brain—A meta-analysis of imaging studies on the self. *Neuroimage.* 2006; 31:440–457. [PubMed: 16466680]
- 18 Sajon B, et al. Delineating self-referential processing from episodic memory retrieval: Common and dissociable networks. *Neuroimage.* 2010; 50:1606–1617. [PubMed: 20123026]
- 19 Buckner RL, Carroll DC. Self-projection and the brain. *Trends in cognitive sciences.* 2007; 11:49–57. [PubMed: 17188554]

- 20 Qin P, Northoff G. How is our self related to midline regions and the default-mode network? *Neuroimage*. 2011; 57:1221–1233. [PubMed: 21609772]
- 21 Whitfield-Gabrieli S, et al. Associations and dissociations between default and self-reference networks in the human brain. *Neuroimage*. 2011; 55:225–232. [PubMed: 21111832]
- 22 Kurczek J, et al. Differential contributions of hippocampus and medial prefrontal cortex to self-projection and self-referential processing. *Neuropsychologia*. 2015; 73:116–126. [PubMed: 25959213]
- 23 Moran JM, Kelley WM, Heatherton TF. What can the organization of the brain's default mode network tell us about self-knowledge? *Front Hum Neurosci*. 2013; 7
- 24 Palombo D, Hayes S, Peterson K, Keane M, Verfaellie M. Medial Temporal Lobe Contributions to Episodic Future Thinking: Scene Construction or Future Projection? *Cereb Cortex*. 2016 Published online December 02, 2016, doi:10.1093/cercor/bhw2381.
- 25 Hassabis D, Kumaran D, Maguire EA. Using Imagination to Understand the Neural Basis of Episodic Memory. *J Neurosci*. 2007; 27:14365–14374. [PubMed: 18160644]
- 26 Hassabis D, Maguire EA. Deconstructing episodic memory with construction. *Trends in Cognitive Sciences*. 2007; 11:299–306. [PubMed: 17548229]
- 27 Hassabis D, Kumaran D, Vann SD, Maguire EA. Patients with hippocampal amnesia cannot imagine new experiences. *Proc Natl Acad Sci*. 2007; 104:1726–1731. [PubMed: 17229836]
- 28 Bird CM, Capponi C, King JA, Doeller CF, Burgess N. Establishing the boundaries: the hippocampal contribution to imagining scenes. *J Neurosci*. 2010; 30:11688–11695. [PubMed: 20810889]
- 29 Nyberg L, Kim AS, Habib R, Levine B, Tulving E. Consciousness of subjective time in the brain. *Proc Natl Acad Sci*. 2010; 107:22356–22359. [PubMed: 21135219]
- 30 Tulving E. *Chronesthesia: Conscious awareness of subjective time* Principles of frontal lobe function Stuss DT, Knight RC, editors Oxford University Press; New York: 2002
- 31 Peer M, Salomon R, Goldberg I, Blanke O, Arzy S. Brain system for mental orientation in space, time, and person. *Proc Natl Acad Sci U S A*. 2015; 112:11072–11077. [PubMed: 26283353]
- 32 Binder JR, Desai RH, Graves WW, Conant LL. Where Is the Semantic System? A Critical Review and Meta-Analysis of 120 Functional Neuroimaging Studies. *Cereb Cortex*. 2009; 19:2767–2796. [PubMed: 19329570]
- 33 Davey J, et al. Automatic and controlled semantic retrieval: TMS reveals distinct contributions of posterior middle temporal gyrus and angular gyrus. *J Neurosci*. 2015; 35:15230–15239. [PubMed: 26586812]
- 34 Humphreys GF, Hoffman P, Visser M, Binney RJ, Ralph MAL. Establishing task-and modality-dependent dissociations between the semantic and default mode networks. *Proc Natl Acad Sci*. 2015; 112:7857–7862. [PubMed: 26056304]
- 35 Vatansever D, et al. Varieties of semantic cognition revealed through simultaneous decomposition of intrinsic brain connectivity and behaviour. *Neuroimage*. 2017; 158:1–11. [PubMed: 28655631]
- 36 Sestieri C, Corbetta M, Romani GL, Shulman GL. Episodic memory retrieval, parietal cortex, and the default mode network: functional and topographic analyses. *J Neurosci*. 2011; 31:4407–4420. [PubMed: 21430142]
- 37 Sestieri C, Shulman GL, Corbetta M. The contribution of the human posterior parietal cortex to episodic memory. *Nat Rev Neurosci*. 2017; 18:183–192. [PubMed: 28209980]
- 38 Rugg MD, Vilberg KL. Brain networks underlying episodic memory retrieval. *Curr Opin Neurobiol*. 2013; 23:255–260. [PubMed: 23206590]
- 39 Foster BL, Rangarajan V, Shirer WR, Parvizi J. Intrinsic and Task-Dependent Coupling of Neuronal Population Activity in Human Parietal Cortex. *Neuron*. 2015; 86:578–590. [PubMed: 25863718]
- 40 Chen J, et al. Shared memories reveal shared structure in neural activity across individuals. *Nat Neurosci*. 2017; 20:115–125. [PubMed: 27918531]
- 41 Hirshhorn M, Grady C, Rosenbaum RS, Winocur G, Moscovitch M. Brain regions involved in the retrieval of spatial and episodic details associated with a familiar environment: an fMRI study. *Neuropsychologia*. 2012; 50:3094–3106. [PubMed: 22910274]

- 42Mars RB, et al. On the relationship between the “default mode network” and the “social brain”. *Front Hum Neurosci.* 2012; 6:179. [PubMed: 22715326]
- 43Spreng R, Andrews-Hanna J. The default network and social cognition. *Brain Mapping: An Encyclopedic Reference Academic Press: Elsevier;* 2015 165169
- 44Schilbach L, Eickhoff SB, Rotarska-Jagiela A, Fink GR, Vogeley K. Minds at rest? Social cognition as the default mode of cognizing and its putative relationship to the “default system” of the brain. *Conscious Cogn.* 2008; 17:457–467. [PubMed: 18434197]
- 45Mitchell JP, Banaji MR, Macrae CN. The link between social cognition and self-referential thought in the medial prefrontal cortex. *J Cogn Neurosci.* 2005; 17:1306–1315. [PubMed: 16197685]
- 46Gilead M, et al. Self-regulation via neural simulation. *Proc Natl Acad Sci.* 2016; 113:10037–10042. [PubMed: 27551094]
- 47Hill PF, Yi R, Spreng RN, Diana RA. Neural congruence between intertemporal and interpersonal self-control: Evidence from delay and social discounting. *Neuroimage.* 2017 Published online September 4, 2017, doi: 2010.1016/j.neuroimage.2017.2008.2071.
- 48Saxe R, Kanwisher N. People thinking about thinking people: the role of the temporo-parietal junction in “theory of mind”. *Neuroimage.* 2003; 19:1835–1842. [PubMed: 12948738]
- 49Tusche A, Smallwood J, Bernhardt BC, Singer T. Classifying the wandering mind: revealing the affective content of thoughts during task-free rest periods. *Neuroimage.* 2014; 97:107–116. [PubMed: 24705200]
- 50Maysless N, Eran A, Shamay-Tsoory SG. Generating original ideas: The neural underpinning of originality. *Neuroimage.* 2015; 116:232–239. [PubMed: 26003860]
- 51Beaty RE, et al. Creativity and the default network: A functional connectivity analysis of the creative brain at rest. *Neuropsychologia.* 2014; 64:92–98. [PubMed: 25245940]
- 52Laird AR, et al. Investigating the functional heterogeneity of the default mode network using coordinate-based meta-analytic modeling. *J Neurosci.* 2009; 29:14496–14505. [PubMed: 19923283]
- 53Leech R, Braga R, Sharp DJ. Echoes of the brain within the posterior cingulate cortex. *J Neurosci.* 2012; 32:215–222. [PubMed: 22219283]
- 54Mars RB, et al. Connectivity-Based Subdivisions of the Human Right “Temporoparietal Junction Area”: Evidence for Different Areas Participating in Different Cortical Networks. *Cereb Cortex.* 2011; 22:894–1903.
- 55Bzdok D, et al. Subspecialization in the human posterior medial cortex. *Neuroimage.* 2015; 106:55–71. [PubMed: 25462801]
- 56Bzdok D, et al. Characterization of the temporo-parietal junction by combining data-driven parcellation, complementary connectivity analyses, and functional decoding. *Neuroimage.* 2013; 81:381–392. [PubMed: 23689016]
- 57Leech R, Kamourieh S, Beckmann CF, Sharp DJ. Fractionating the default mode network: distinct contributions of the ventral and dorsal posterior cingulate cortex to cognitive control. *J Neurosci.* 2011; 31:3217–3224. [PubMed: 21368033]
- 58Dastjerdi M, et al. Differential electrophysiological response during rest, self-referential, and non-self-referential tasks in human posteromedial cortex. *Proc Natl Acad Sci U S A.* 2011; 108:3023–3028. [PubMed: 21282630]
- 59Seghier ML, Fagan E, Price CJ. Functional Subdivisions in the Left Angular Gyrus Where the Semantic System Meets and Diverges from the Default Network. *J Neurosci.* 2010; 30:16809–16817. [PubMed: 21159952]
- 60Braga RM, Buckner RL. Parallel Interdigitated Distributed Networks within the Individual Estimated by Intrinsic Functional Connectivity. *Neuron.* 2017; 95:457–471. e455. [PubMed: 28728026]
- 61Braga RM, Sharp DJ, Leeson C, Wise RJ, Leech R. Echoes of the Brain within Default Mode, Association, and Heteromodal Cortices. *J Neurosci.* 2013; 33:14031–14039. [PubMed: 23986239]
- 62Utevsky AV, Smith DV, Huettel SA. Precuneus Is a Functional Core of the Default-Mode Network. *J Neurosci.* 2014; 34:932–940. [PubMed: 24431451]

- 63 Ramot M, et al. A widely distributed spectral signature of task-negative electrocorticography responses revealed during a visuomotor task in the human cortex. *J Neurosci.* 2012; 32:10458–10469. [PubMed: 22855795]
- 64 Bellana B, Liu ZX, Diamond N, Grady C, Moscovitch M. Similarities and differences in the default mode network across rest, retrieval, and future imagining. *Hum Brain Mapp.* 2017; 38:1155–1171. [PubMed: 27774695]
- 65 Spreng RN, Grady CL. Patterns of Brain Activity Supporting Autobiographical Memory, Prospection, and Theory of Mind, and Their Relationship to the Default Mode Network. *J Cogn Neurosci.* 2009; 22:1112–1123.
- 66 D'Argembeau A, et al. The neural basis of personal goal processing when envisioning future events. *J Cogn Neurosci.* 2010; 22:1701–1713. [PubMed: 19642887]
- 67 Tamir DI, Bricker AB, Dodell-Feder D, Mitchell JP. Reading fiction and reading minds: the role of simulation in the default network. *Soc Cogn Affect Neurosci.* 2015; 11:215–224. [PubMed: 26342221]
- 68 Abraham A, Schubotz RI, von Cramon DY. Thinking about the future versus the past in personal and non-personal contexts. *Brain Res.* 2008; 1233:106–119. [PubMed: 18703030]
- 69 Szpunar KK, Watson JM, McDermott KB. Neural substrates of envisioning the future. *Proc Natl Acad Sci.* 2007; 104:642–647. [PubMed: 17202254]
- 70 Andrews-Hanna JR, Saxe R, Yarkoni T. Contributions of episodic retrieval and mentalizing to autobiographical thought: Evidence from functional neuroimaging, resting-state connectivity, and fMRI meta-analyses. *Neuroimage.* 2014; 91:324–335. [PubMed: 24486981]
- 71 Preminger S, Harmelech T, Malach R. Stimulus-free thoughts induce differential activation in the human default network. *Neuroimage.* 2011; 54:1692–1702. [PubMed: 20728555]
- 72 Harrison BJ, et al. Consistency and functional specialization in the default mode brain network. *Proc Natl Acad Sci.* 2008; 105:9781–9786. [PubMed: 18621692]
- 73 Shapira-Lichter I, Oren N, Jacob Y, Gruberger M, Hendler T. Portraying the unique contribution of the default mode network to internally driven mnemonic processes. *Proc Natl Acad Sci.* 2013; 110:4950–4955. [PubMed: 23479650]
- 74 Karapanagiotidis T, Bernhardt BC, Jefferies E, Smallwood J. Tracking thoughts: Exploring the neural architecture of mental time travel during mind-wandering. *Neuroimage.* 2017; 147:272–281. [PubMed: 27989779]
- 75 Smallwood J, et al. Representing Representation: Integration between the Temporal Lobe and the Posterior Cingulate Influences the Content and Form of Spontaneous Thought. *PLoS One.* 2016; 11:e0152272. [PubMed: 27045292]
- 76 Gorgolewski KJ, et al. A correspondence between individual differences in the brain's intrinsic functional architecture and the content and form of self-generated thoughts. *PLoS One.* 2014; 9:e97176. [PubMed: 24824880]
- 77 Andrews-Hanna JR, Reidler JS, Huang C, Buckner RL. Evidence for the default network's role in spontaneous cognition. *J Neurophysiol.* 2010; 104:322–335. [PubMed: 20463201]
- 78 Doucet G, et al. Patterns of hemodynamic low-frequency oscillations in the brain are modulated by the nature of free thought during rest. *Neuroimage.* 2012; 59:3194–3200. [PubMed: 22155378]
- 79 Poerio GL, et al. The role of the default mode network in component processes underlying the wandering mind. *Soc Cogn Affect Neurosci.* 2017 nsx041.
- 80 Medea B, et al. How do we decide what to do? Resting-state connectivity patterns and components of self-generated thought linked to the development of more concrete personal goals. *Exp Brain Res.* 2016:1–13.
- 81 de Caso I, Poerio G, Jefferies E, Smallwood J. That's me in the spotlight—Neural basis of individual differences in self-consciousness. *Soc Cogn Affect Neurosci.* 2017
- 82 Andrews-Hanna JR, Reidler JS, Sepulcre J, Poulin R, Buckner RL. Functional-anatomic fractionation of the brain's default network. *Neuron.* 2010; 65:550–562. [PubMed: 20188659]
- 83 Kim S, Dede AJ, Hopkins RO, Squire LR. Memory, scene construction, and the human hippocampus. *Proc Natl Acad Sci.* 2015; 112:4767–4772. [PubMed: 25825712]
- 84 Xu X, Yuan H, Lei X. Activation and connectivity within the default mode network contribute independently to future-oriented thought. *Scientific Reports.* 2016; 6

- 85 Summerfield JJ, Hassabis D, Maguire EA. Cortical midline involvement in autobiographical memory. *Neuroimage*. 2009; 44:1188–1200. [PubMed: 18973817]
- 86 Irish M, Piguet O. The pivotal role of semantic memory in remembering the past and imagining the future. *Front Behav Neurosci*. 2013; 7:27. [PubMed: 23565081]
- 87 Burianova H, Grady CL. Common and unique neural activations in autobiographical, episodic, and semantic retrieval. *J Cogn Neurosci*. 2007; 19:1520–1534. [PubMed: 17714013]
- 88 Woo C-W, Krishnan A, Wager TD. Cluster-extent based thresholding in fMRI analyses: pitfalls and recommendations. *Neuroimage*. 2014; 91:412–419. [PubMed: 24412399]
- 89 Eklund A, Nichols TE, Knutsson H. Cluster failure: Why fMRI inferences for spatial extent have inflated false-positive rates. *Proc Natl Acad Sci*. 2016 201602413.
- 90 Spreng RN, Mar RA, Kim ASN. The Common Neural Basis of Autobiographical Memory, Prospection, Navigation, Theory of Mind, and the Default Mode: A Quantitative Meta-analysis. *J Cogn Neurosci*. 2008; 21:489–510.
- 91 Kriegeskorte N, Simmons WK, Bellgowan PSF, Baker CI. Circular analysis in systems neuroscience: the dangers of double dipping. *Nat Neurosci*. 2009; 12:535–540. [PubMed: 19396166]
- 92 Kelley WM, et al. Finding the self? An event-related fMRI study. *J Cogn Neurosci*. 2002; 14:785–794. [PubMed: 12167262]
- 93 Goldberg II, Harel M, Malach R. When the Brain Loses Its Self: Prefrontal Inactivation during Sensorimotor Processing. *Neuron*. 2006; 50:329–339. [PubMed: 16630842]
- 94 Murray RJ, Schaer M, Debbané M. Degrees of separation: A quantitative neuroimaging meta-analysis investigating self-specificity and shared neural activation between self-and other-reflection. *Neurosci Biobehav Rev*. 2012; 36:1043–1059. [PubMed: 22230705]
- 95 Kriegeskorte N, Kievit RA. Representational geometry: integrating cognition, computation, and the brain. *Trends in Cognitive Sciences*. 2013; 17:401–412. [PubMed: 23876494]
- 96 Raizada RD, Kriegeskorte N. Pattern-information fMRI: New questions which it opens up and challenges which face it. *International Journal of Imaging Systems and Technology*. 2010; 20:31–41.
- 97 Oosterhof NN, Wiggett AJ, Diedrichsen J, Tipper SP, Downing PE. Surface-based information mapping reveals crossmodal vision–action representations in human parietal and occipitotemporal cortex. *J Neurophysiol*. 2010; 104:1077–1089. [PubMed: 20538772]
- 98 Aminoff EM, Kveraga K, Bar M. The role of the parahippocampal cortex in cognition. *Trends in Cognitive Sciences*. 2013; 17:379–390. [PubMed: 23850264]
- 99 Epstein R, Kanwisher N. A cortical representation of the local visual environment. *Nature*. 1998; 392:598–601. [PubMed: 9560155]
- 100 Epstein RA. Parahippocampal and retrosplenial contributions to human spatial navigation. *Trends in Cognitive Sciences*. 2008; 12:388–396. [PubMed: 18760955]
- 101 Baldassano C, Esteva A, Fei-Fei L, Beck DM. Two Distinct Scene-Processing Networks Connecting Vision and Memory. *eNeuro*. 2016; 3:1–14.
- 102 Price CJ. A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. *Neuroimage*. 2012; 62:816–847. [PubMed: 22584224]
- 103 Fedorenko E, Hsieh P-J, Nieto-Castañón A, Whitfield-Gabrieli S, Kanwisher N. New Method for fMRI Investigations of Language: Defining ROIs Functionally in Individual Subjects. *J Neurophysiol*. 2010; 104:1177–1194. [PubMed: 20410363]
- 104 Vigneau M, et al. Meta-analyzing left hemisphere language areas: Phonology, semantics, and sentence processing. *Neuroimage*. 2006; 30:1414–1432. [PubMed: 16413796]
- 105 Fedorenko E, Thompson-Schill SL. Reworking the language network. *Trends in Cognitive Sciences*. 2014; 18:120–126. [PubMed: 24440115]
- 106 Friederici AD. The brain basis of language processing: from structure to function. *Physiol Rev*. 2011; 91:1357–1392. [PubMed: 22013214]
- 107 Seghier ML. The Angular Gyrus Multiple Functions and Multiple Subdivisions. *The Neuroscientist*. 2013; 19:43–61. [PubMed: 22547530]

- 108 Simony E, et al. Dynamic reconfiguration of the default mode network during narrative comprehension. *Nat Commun.* 2016; 7
- 109 Bookheimer S. Functional MRI of language: new approaches to understanding the cortical organization of semantic processing. *Annu Rev Neurosci.* 2002; 25:151–188. [PubMed: 12052907]
- 110 Patterson K, Nestor PJ, Rogers TT. Where do you know what you know? The representation of semantic knowledge in the human brain. *Nat Rev Neurosci.* 2007; 8:976–987. [PubMed: 18026167]
- 111 Ross LA, Olson IR. What's unique about unique entities? An fMRI investigation of the semantics of famous faces and landmarks. *Cereb Cortex.* 2011; 22:2005–2015. [PubMed: 22021913]
- 112 Axelrod V, Yovel G. Successful decoding of famous faces in the Fusiform Face Area. *PLoS One.* 2015; 10:e0117126. [PubMed: 25714434]
- 113 Wirth M, et al. Semantic memory involvement in the default mode network: a functional neuroimaging study using independent component analysis. *Neuroimage.* 2011; 54:3057–3066. [PubMed: 20965253]
- 114 Jackson RL, Hoffman P, Pobric G, Ralph MAL. The semantic network at work and rest: Differential connectivity of anterior temporal lobe subregions. *J Neurosci.* 2016; 36:1490–1501. [PubMed: 26843633]
- 115 Krieger-Redwood K, et al. Down but not out in posterior cingulate cortex: Deactivation yet functional coupling with prefrontal cortex during demanding semantic cognition. *Neuroimage.* 2016; 141:366–377. [PubMed: 27485753]
- 116 Margulies DS, et al. Situating the default-mode network along a principal gradient of macroscale cortical organization. *Proc Natl Acad Sci.* 2016; 113:12574–12579. [PubMed: 27791099]
- 117 Hasson U, Chen J, Honey CJ. Hierarchical process memory: memory as an integral component of information processing. *Trends in Cognitive Sciences.* 2015; 19:304–313. [PubMed: 25980649]
- 118 Golland Y, et al. Extrinsic and intrinsic systems in the posterior cortex of the human brain revealed during natural sensory stimulation. *Cereb Cortex.* 2007; 17:766–777. [PubMed: 16699080]
- 119 Benoit RG, Schacter DL. Specifying the core network supporting episodic simulation and episodic memory by activation likelihood estimation. *Neuropsychologia.* 2015; 75:450–457. [PubMed: 26142352]
- 120 Grady CL, et al. A multivariate analysis of age-related differences in default mode and task-positive networks across multiple cognitive domains. *Cereb Cortex.* 2009; 20:1432–1447. [PubMed: 19789183]
- 121 Salomon R, Levy DR, Malach R. Deconstructing the default: Cortical subdivision of the default mode/intrinsic system during self-related processing. *Hum Brain Mapp.* 2013; 35:1491–1502. [PubMed: 23568328]
- 122 Craven KM, Kanwisher N. Mental Imagery of Faces and Places Activates Corresponding Stimulus-Specific Brain Regions. *J Cogn Neurosci.* 2000; 12:1013–1023. [PubMed: 11177421]
- 123 Cichy RM, Heinze J, Haynes J-D. Imagery and perception share cortical representations of content and location. *Cereb Cortex.* 2012; 22:372–380. [PubMed: 21666128]
- 124 Reddy L, Tsuchiya N, Serre T. Reading the mind's eye: decoding category information during mental imagery. *Neuroimage.* 2010; 50:818–825. [PubMed: 20004247]
- 125 Bar M, Aminoff E, Mason M, Fenske M. The units of thought. *Hippocampus.* 2007; 17:420–428. [PubMed: 17455334]
- 126 Chavez RS, Heatherton TF. Representational similarity of social and valence information in the medial pFC. *J Cogn Neurosci.* 2015; 27:73–82. [PubMed: 25100218]
- 127 Poldrack RA, et al. Scanning the horizon: towards transparent and reproducible neuroimaging research. *Nature Reviews Neuroscience.* 2017; 18:115–126. [PubMed: 28053326]
- 128 Axelrod V, Yovel G. Hierarchical Processing of Face Viewpoint in Human Visual Cortex. *J Neurosci.* 2012; 32:2442–2452. [PubMed: 22396418]
- 129 Axelrod V, Bar M, Rees G, Yovel G. Neural correlates of subliminal language processing. *Cereb Cortex.* 2015; 25:2160–2169. [PubMed: 24557638]

- 130 Axelrod V. On the domain-specificity of the visual and non-visual face-selective regions. *Eur J Neurosci*. 2016; 44:2049–2063. [PubMed: 27255921]
- 131 Ashburner J, Friston KJ. Unified segmentation. *Neuroimage*. 2005; 26:839–851. [PubMed: 15955494]
- 132 Song X-W, et al. REST: a toolkit for resting-state functional magnetic resonance imaging data processing. *PLoS One*. 2011; 6:e25031. [PubMed: 21949842]
- 133 Siuda-Krzywicka K, et al. Massive cortical reorganization in sighted Braille readers. *eLife*. 2016; 5:e10762. [PubMed: 26976813]
- 134 Wang L, et al. Changes in hippocampal connectivity in the early stages of Alzheimer's disease: evidence from resting state fMRI. *Neuroimage*. 2006; 31:496–504. [PubMed: 16473024]
- 135 Zald DH, et al. Midbrain dopamine receptor availability is inversely associated with novelty-seeking traits in humans. *J Neurosci*. 2008; 28:14372–14378. [PubMed: 19118170]
- 136 Brett M, , Anton J, , Valabregue R, , Poline J. Region of interest analysis using an SPM toolbox. Paper presented at the 8th International Conference on Functional Mapping of the Human Brain; Sendai, Japan. Jun, 2002
- 137 Axelrod V. Minimizing bugs in cognitive neuroscience programming. *Frontiers in psychology*. 2014; 5:1435. [PubMed: 25566120]
- 138 Craddock RC, James GA, Holtzheimer PE, Hu XP, Mayberg HS. A whole brain fMRI atlas generated via spatially constrained spectral clustering. *Hum Brain Mapp*. 2012; 33:1914–1928. [PubMed: 21769991]
- 139 Nili H, et al. A toolbox for representational similarity analysis. *PLoS Comput Biol*. 2014; 10:e1003553. [PubMed: 24743308]
- 140 Etzel JA, Zacks JM, Braver TS. Searchlight analysis: Promise, pitfalls, and potential. *Neuroimage*. 2013; 78:261–269. [PubMed: 23558106]
- 141 Björnsdotter M, Rylander K, Wessberg J. A Monte Carlo method for locally multivariate brain mapping. *Neuroimage*. 2011; 56:508–516. [PubMed: 20674749]

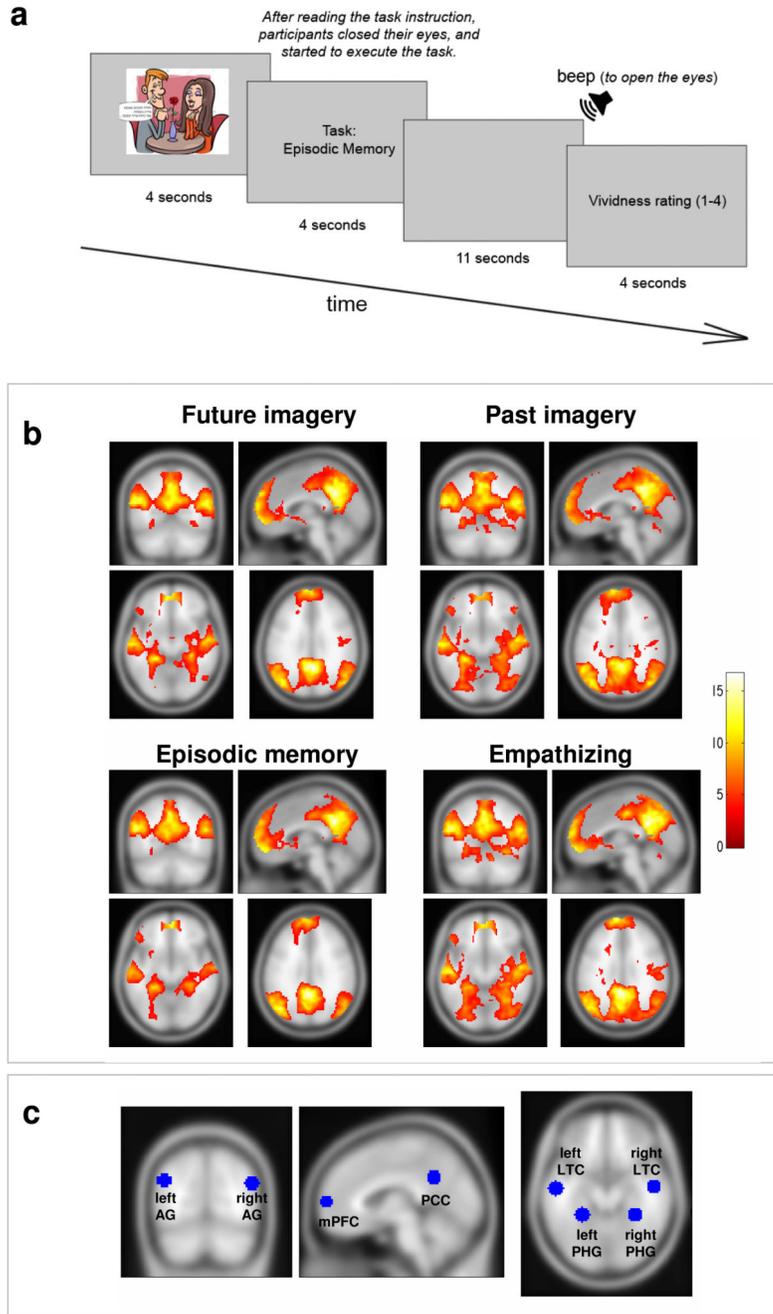
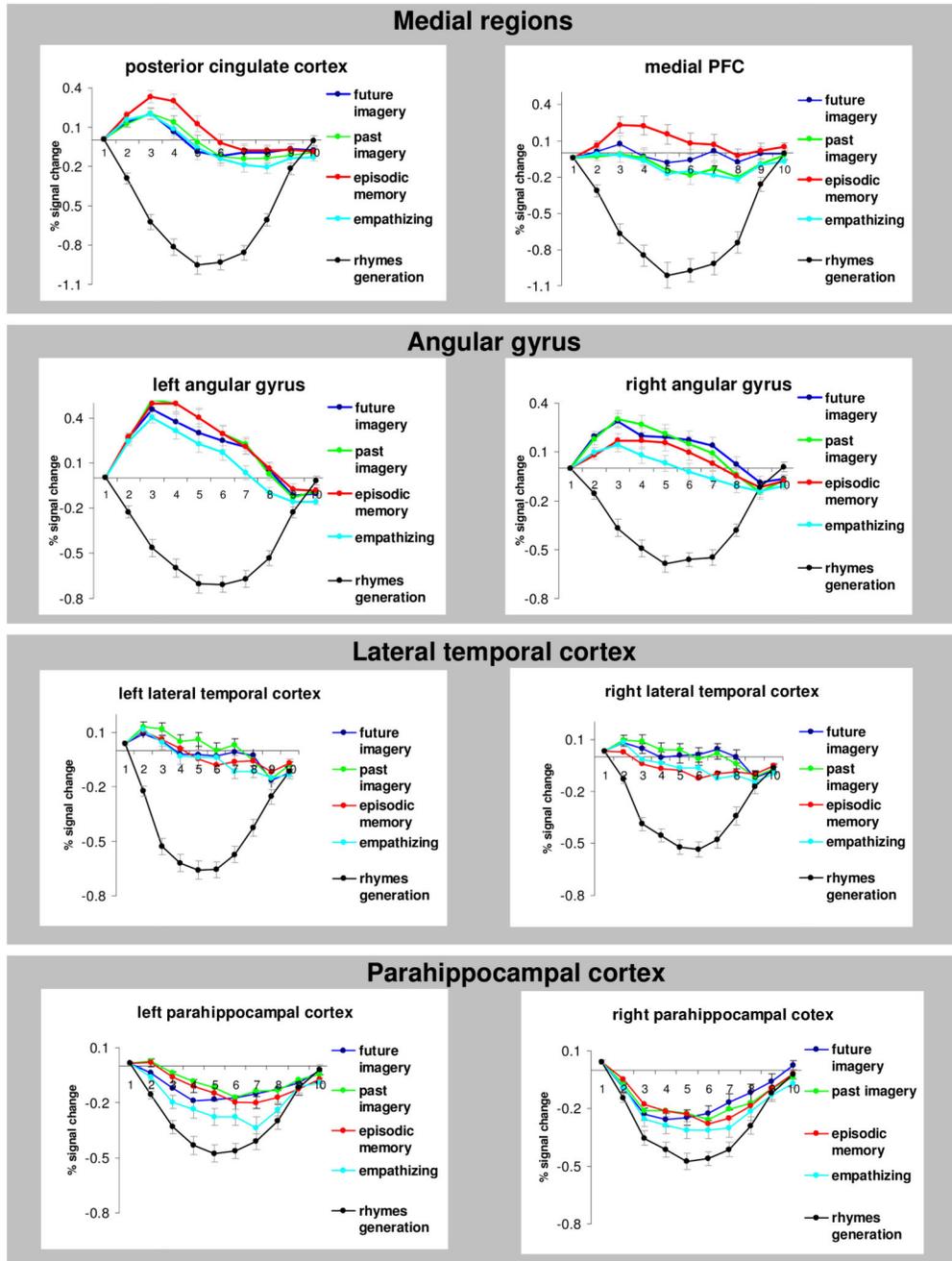


Figure 1. Experiment 1: Schematic flow of the experimental trial, results of the group-level analysis of four internal tasks and location of Regions of interest (ROIs). (a) Schematic flow of the trial (from left to right). After seeing a picture, the participants received the task instruction, and started to execute the task with their eyes closed. The task execution ended with a beep sound, followed by vividness rating of the experience. There were five tasks (conditions): imagine what happened before ("past imagery") or after ("future imagery") the depicted scene, recall a personal episodic memory related to the depicted scene ("episodic memory"),

imagine yourself in the place of the person in the image ("empathizing"), and generate words that rhyme with a provided word (baseline condition; the target word was provided at the stage of task instruction). Each of the pictures was repeated once for each of the five experimental conditions. Notably, the image was presented in all conditions including baseline, to preserve identical visual stimulation. Accordingly, the contrast between internal task and baseline does not include the activity elicited by visual scene. (b) Results of the group-level random effect analysis of Experiment 1 ($n=36$): Four tasks of interest (episodic memory, future imagery, past imagery, and empathizing) contrasted separately against the rhyme-generation baseline task (voxel-wise primary threshold p -value < 0.001 and a cluster-level threshold p -value < 0.05 , corrected. Note the typical DMN activations for all four conditions. Statistical maps were overlaid on T1 SPM template brain. (c) Average location of the ROIs. The ROIs used in the analysis were defined as individual clusters and were not spherical (see Methods). Locations here represent average location across participants (see also Supplementary Table 1). Abbreviations: mPFC is medial prefrontal cortex, PCC is posterior cingulate cortex, AG is angular gyrus, LTC is lateral temporal cortex, and PHC is parahippocampal cortex.

**Figure 2.**

Experiment 1 (n=36): Percent signal change time-courses for five experimental conditions ("future imagery," "past imagery," "episodic memory," "empathizing," and "rhyme generation") in the DMN. The units of the X axis are TRs (2.5 sec). The first bin of the X axis corresponds to the onset of task instruction (see Fig. 1a). Error bars represent the standard error of the mean. Note: a) large differences between four internal tasks and rhymes generation baseline condition; b) differences in shape of time-courses across internal tasks: a clear positive and inverted U-shape response in the PCC, angular gyrus, and mPFC in

"episodic memory" condition, and a clear negative and U-shape response in the PHC; c) a higher response to "episodic memory" compared to other conditions in the mPFC and PCC.

Experiment 2: Self-referential processing

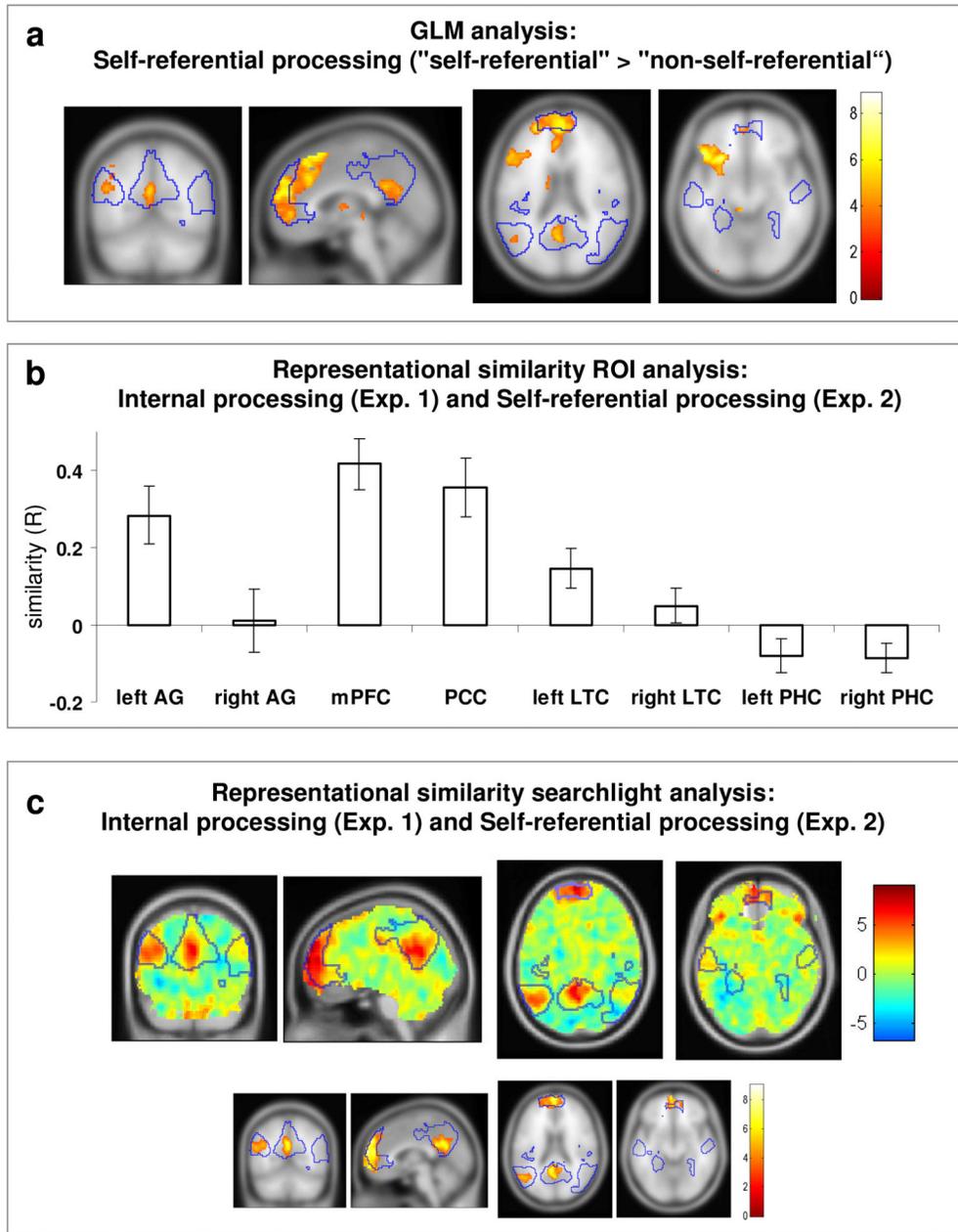


Figure 3. Experiment 2 (n=34): Self-referential processing. (a) Group-level random effect analysis of self-referential processing of Experiment 2 (contrast: "self-referential" > "non-self-referential"). Statistical threshold: primary voxel-wised threshold $p < 0.001$, $p < 0.05$, cluster size corrected. The blue contour line denotes the DMN identified using the first (independent) session of the experiment ("four internal conditions > baseline"). Note, that significant clusters within the DMN were found in the mPFC, PCC, and left angular gyrus, but not in the PHC, LTC, and right angular gyrus. (b) ROI representational similarity

analysis between internal processing (Experiment 1, four internal tasks combined) and self-referential processing (Experiment 2). The values reflect the average across participants within-ROI Spearman correlation between the internal processing contrast of Experiment 1 (four internal tasks > baseline) and the self-referential processing contrast of Experiment 2 ("self-referential" > "non-self-referential"). Similarity values denote Fischer z-transformed correlation results. Note, high similarity values in the mPFC, PCC, and to a lesser extent in the left angular gyrus. Significance above zero was established using one sample, two-tail t-test (multiple comparison Bonferroni correction for number of tested regions, $N=8$, $\alpha=0.05/8=0.00625$). For regional specificity and task specificity analyses, see the Results section. Error bars represent standard error of the mean. For individual data, see Supplementary Figure 1a. (c) Searchlight ROI representational similarity analysis between internal processing (Experiment 1, four internal tasks combined) and self-referential processing (Experiment 2). Top: unthresholded statistical results map; Bottom: thresholded significant clusters (primary voxel-wised threshold $p < 0.001$, $p < 0.05$, cluster size corrected). Note the high similarity in the mPFC, PCC, and left posterior parietal cortex, but not in other regions of the cortex. Also note the strong left lateralization in the posterior parietal cortex.

Experiment 3: Scene construction

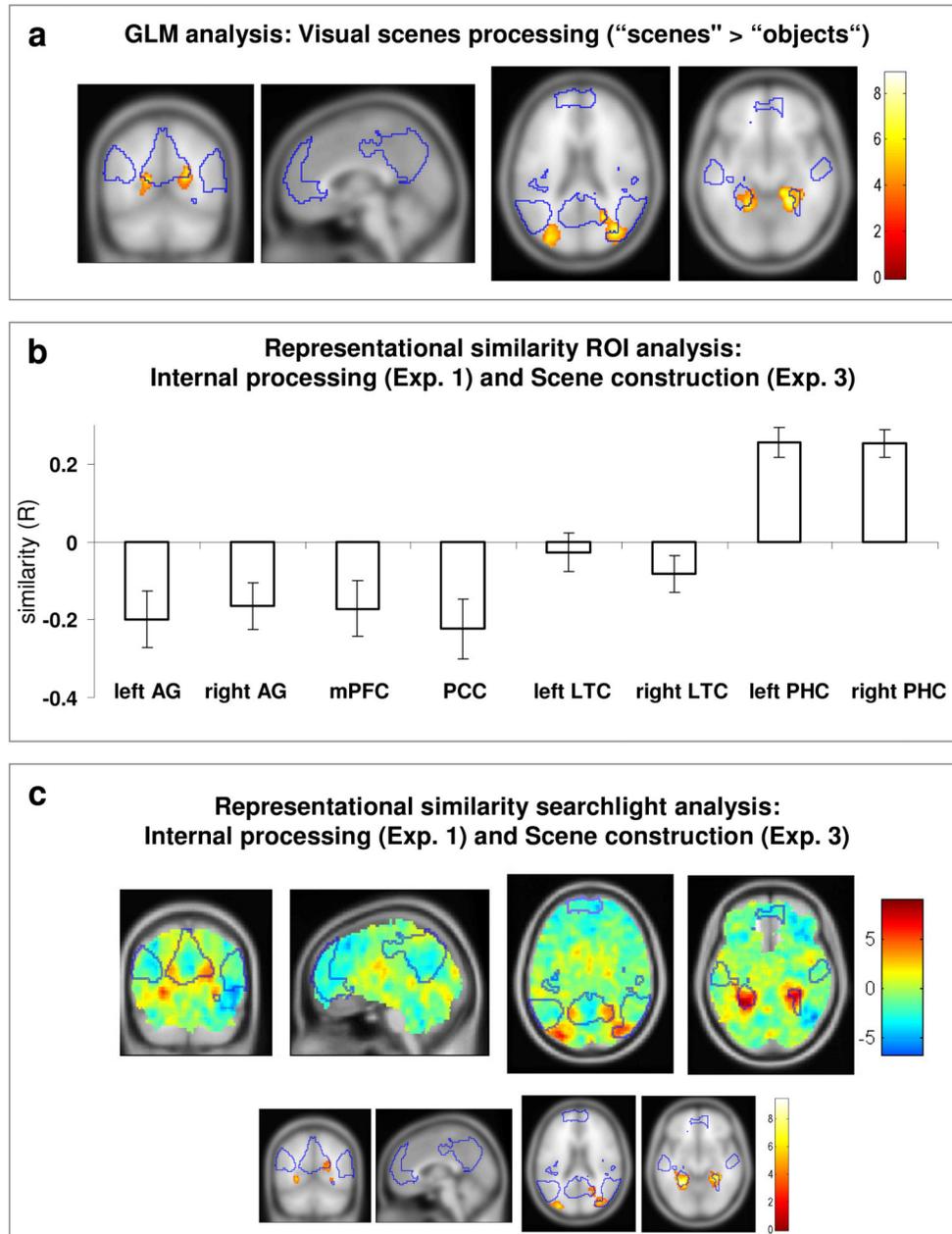


Figure 4. Experiment 3 (n=33): Scene construction. (a) Group-level random effect analysis, "scenes" > "objects" contrast. Statistical threshold: primary voxel-wise threshold $p < 0.001$, $p < 0.05$, cluster size corrected. Note, that the largest and most significant clusters within the DMN were found in the PHC. (b) ROI representational similarity analysis between internal processing (Experiment 1, four internal tasks combined) and "scenes" > "objects" contrast (Experiment 3). Note, much higher than zero similarity values in the bilateral PHC. Significance above zero was established using one sample, two-tail t-test (multiple

comparison Bonferroni correction for number of tested regions, $N=8$, $\alpha=0.05/8=0.00625$). Error bars represent standard error of the mean. For individual data, see Supplementary Figure 1b. (c) Searchlight ROI representational similarity analysis between internal processing (Experiment 1, four internal tasks combined) and "scenes" > "objects" contrast (Experiment 3). Top: unthresholded statistical results map; Bottom: thresholded significant clusters (primary voxel-wised threshold $p < 0.001$, $p < 0.05$, cluster size corrected). Note the high similarity in the PHC, and to a lesser extent in the retrosplenial cortex and middle occipital gyrus, but not in other regions of the cortex.

Experiment 4: Language-related processing

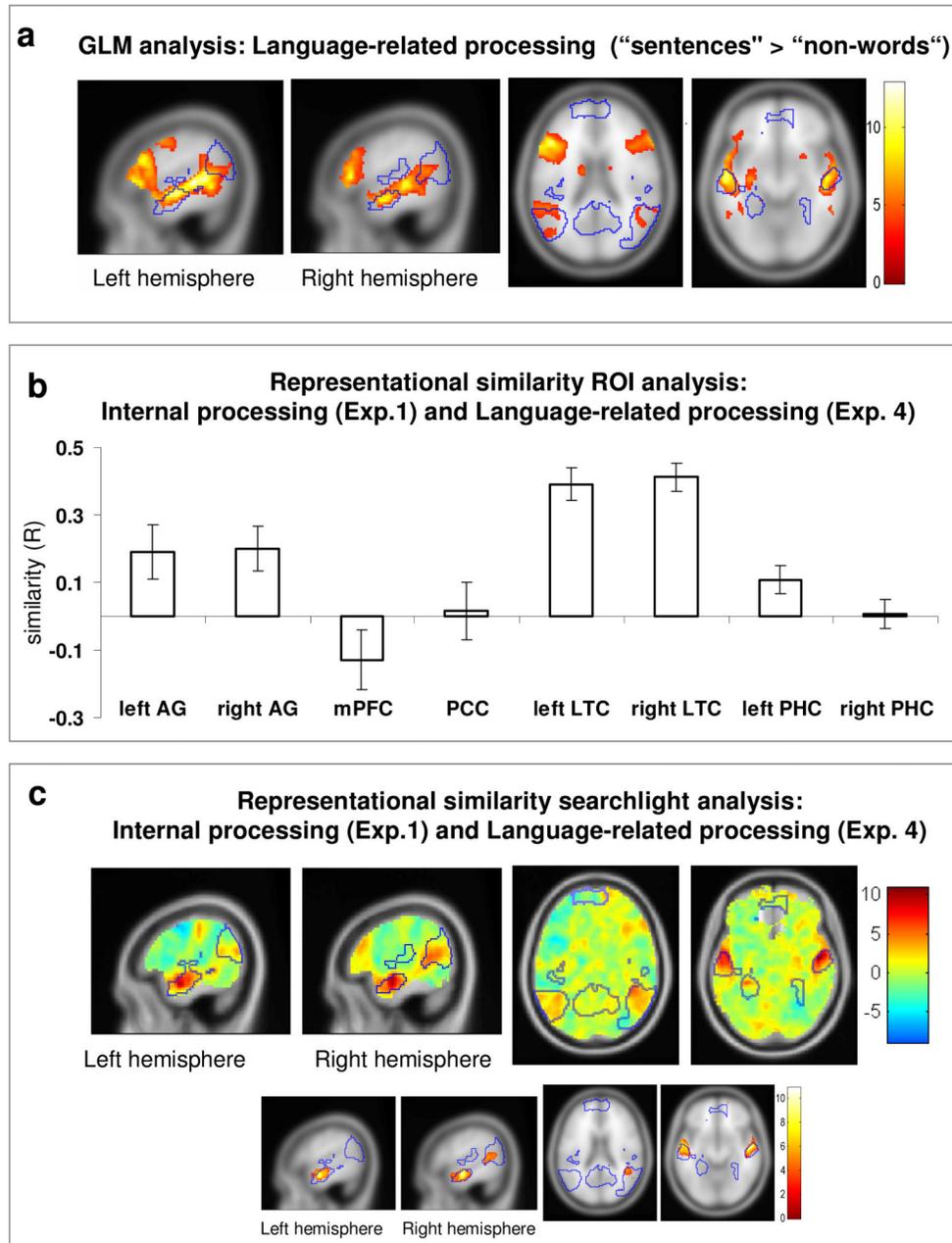


Figure 5. Experiment 4 (n=34): Language-related processing. (a) Group-level random effect analysis of language-related processing of Experiment 4 (contrast: meaningful sentences > meaningless non-words). Statistical threshold: primary voxel-wised threshold $p < 0.001$, $p < 0.05$, cluster size corrected. Note, that the largest and most significant clusters within the DMN were found in the LTC. (b) ROI representational similarity analysis between internal processing (Experiment 1, four internal tasks combined) and language-related processing (meaningful sentences > meaningless non-words, Experiment 4). Note, highest similarity

values in the bilateral LTC. Significance above zero was established using one sample, two-tail t-test (multiple comparison Bonferroni correction for number of tested regions, $N=8$, $\alpha=0.05/8=0.00625$). Error bars represent standard error of the mean. For individual data, see Supplementary Figure 1c. (c) Searchlight ROI representational similarity analysis between internal processing (Experiment 1, four internal tasks combined) and language-related processing (meaningful sentences > meaningless non-words, Experiment 4). Top: unthresholded statistical results map; Bottom: thresholded significant clusters (primary voxel-wised threshold $p < 0.001$, $p < 0.05$, cluster size corrected). Note the highest similarity in the bilateral LTC.

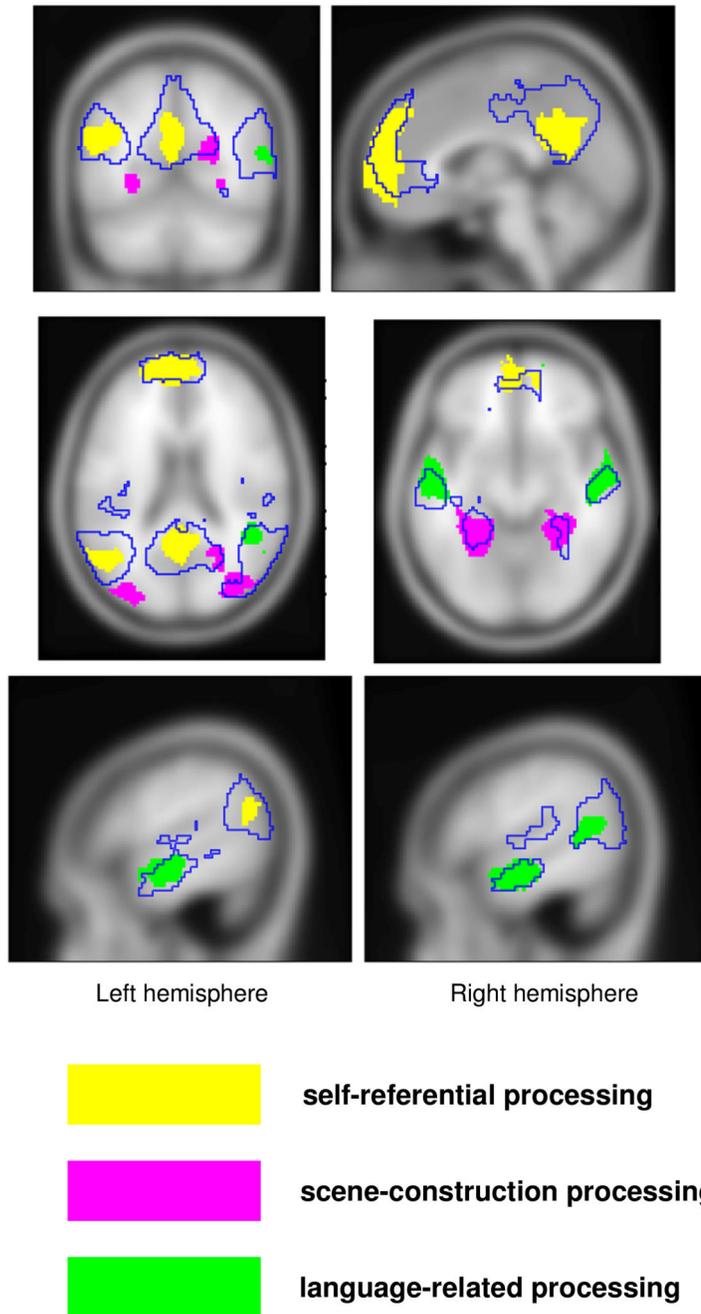


Figure 6.

Summary results: neural loci of three cognitive processes. Results reflect thresholded and binarized maps of corresponding searchlight representational analyses (Figs. 3c, 4c and 5c). The three cognitive processes are self-referential processing (yellow color), mental scene construction (magenta color), and language-related processing (green color). Note that cognitive systems had specific loci (i.e., no spatial overlap between cognitive systems).